

PHENOMENOLOGY OF SUSY WITH INTERMEDIATE SCALE PHYSICS

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The presence of fields at an intermediate scale between the Electroweak and the Grand Unification scale modifies the evolution of the gauge couplings and consequently the running of other parameters of the Minimal Supersymmetric Standard Model, such as gauginos and scalar masses. The net effect is a modification of the low energy spectrum which affects both the collider phenomenology and the dark matter relic density.

1 Introduction

The presence of new physics at a scale intermediate between the electroweak (EW) and the grand unified theory (GUT) scale is common to many supersymmetric (SUSY) models. For example, in order to give mass to the neutrinos, the minimal supersymmetric standard model (MSSM) must be extended. The simplest extension consists in the addition of 2 or 3 chiral superfields which are singlets under the standard model (SM) gauge group (type I seesaw¹), but other extensions are possible, such as the addition of a pair of $\mathbf{15} + \overline{\mathbf{15}}$ SU(5) representations (type II)² or 1 (or 2 or 3) $\mathbf{24}$ (type III)^{3,4}. Except for the singlet case, the presence of new chiral superfields (and, in general, of new fields) at an intermediate scale, affects the running of the MSSM parameters, with a consequent distortion of the low energy SUSY spectrum. Other examples are models where the breaking of the GUT symmetry to the SM one is realized through intermediate steps or flavour models with messengers. In the present work we restrict to consider only chiral superfields at the intermediate scale: as we will see, their main effect is to increase the value of the unified gauge coupling. The presence of gauge fields would drive the result in the opposite direction. However, as long as the net effect is the enhancement of the unified coupling, the results shown here will be qualitatively valid also in the presence of vector fields. In the following we will describe the main effects on the running of the MSSM parameters as well as some phenomenological consequences. We redirect the readers to Ref.⁵ for an extended analysis.

2 MSSM running with intermediate scale

In order to maintain gauge coupling unification, we assume that only chiral superfields in complete vector-like representations of SU(5) are present at the intermediate scale M_I . Even if the unification is preserved, the running of gauge couplings is deflected, above the scale M_I , by the presence of the new fields, as can be observed in the left panel of Fig. 1. The net effect is an

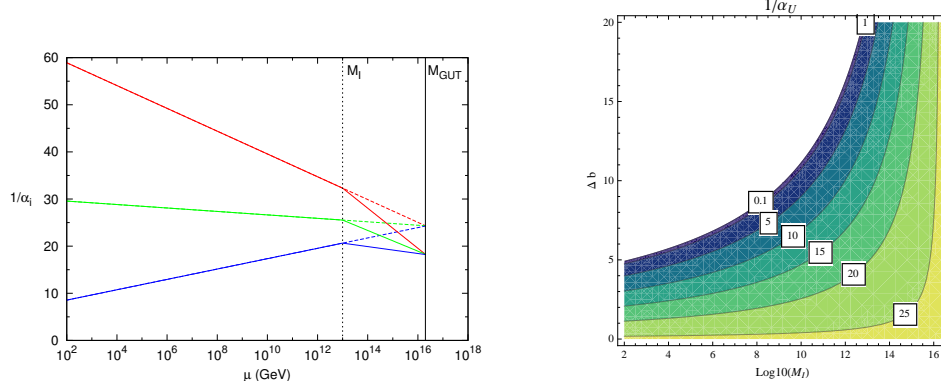


Figure 1: Left: modification of the gauge couplings running in the presence of matter at the intermediate scale $M_I = 10^{13}$ GeV with $\Delta b = 5$ (corresponding, for instance, to a copy of **24**); the dashed lines correspond to the MSSM running. Right: contours on the plane M_I - Δb of the inverse of the unified gauge coupling $1/\alpha_U$.

increment of the unified gauge coupling, as can be seen by solving 1 loop RGEs:

$$\frac{1}{\alpha_U} = \frac{1}{\alpha_i(M_Z)} - \frac{b_i^{SM}}{2\pi} \ln \frac{M_S}{M_Z} - \frac{b_i^0}{2\pi} \ln \frac{M_{GUT}}{M_S} - \frac{\Delta b}{2\pi} \ln \frac{M_{GUT}}{M_I} \equiv \frac{1}{\alpha_U^0} - \frac{\Delta b}{2\pi} \ln \frac{M_{GUT}}{M_I}, \quad (1)$$

where α_U^0 is the unified coupling in the MSSM without intermediate scale ($\alpha_U^0 \simeq 1/25$), $b_i^{SM} = (41/10, -19/6, -7)$ and $b_i^0 = (33/5, 1, -3)$ are respectively the SM and MSSM β -function coefficients for α_i ($i = 1, 2, 3$), Δb is the universal contribution of the additional fields at M_I , given by the sum of the Dynkin indexes of the SU(5) representations, and M_S is the typical low-energy SUSY scale. From Eq. (1), we see that, since $\Delta b \geq 0$ for chiral superfields, the unified coupling α_U is in general larger than the MSSM one.

The increment of α_U is the principal effect of the presence of the intermediate scale and the one which drives all the others. Moreover, by requiring the perturbativity of α_U up to the GUT scale, a large portion of the parameter space can already be excluded, as it is shown in the right panel of Fig. 1, where the white area corresponds to a Landau pole below M_{GUT} . Notice that we are considering 1 loop RGEs. We have checked⁵ that the consequence of two loops running is to strengthen the effect especially close to the Landau pole, while it is almost irrelevant for low Δb and/or large M_I . The perturbativity bounds are then slightly stronger than the ones shown here and the allowed region is consequently smaller (also for the other plots in the following).

Let us now move to consider the effect of the intermediate scale on the other MSSM parameters. Since the RGEs of gaugino masses M_i are strictly related to the ones of the gauge couplings, the increase of α_i above M_I will determine a faster running of each M_i . However, since we are assuming gaugino mass unification, the MSSM low energy ratio of gaugino masses will be maintained and the same MSSM low energy spectrum could be obtained by a simple rescaling of the unified gaugino mass $M_{1/2}$, which would become larger. Then, if only gauginos were there, no interesting observable effect would be produced.

On the other hand, if we consider scalar masses, we observe a different situation: the increment of gauge couplings and gaugino masses above M_I will determine an increase of the low energy scalar masses with respect to the MSSM case, for the same low energy gaugino mass spectra. This is because, to obtain the same low energy gaugino masses, a higher value for $M_{1/2}$ is needed which, together with the larger values of α_i above M_I , enhances the gauge part of the running of scalar masses in the upper part of the RG flow, generating larger values for low energy masses. In a nutshell, the net effect of the intermediate scale is to increase the ratio of scalar over gaugino masses. This is shown in Fig. 2, where the ratio of the first generations left-handed squark over the gluino mass is plotted.

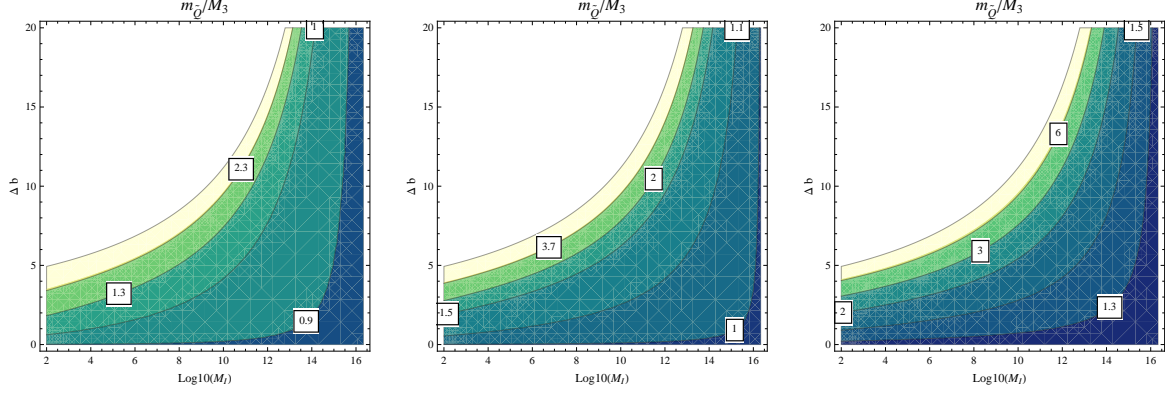


Figure 2: Ratio of the 1st or 2nd generation LH squarks over the gluino mass M_3 for $m_{\tilde{Q}}/M_3 = 0, 1, 2$ at M_{GUT} .

This has interesting phenomenological consequences, both for what concerns SUSY searches at the LHC and for the dark matter (DM) phenomenology.

3 LHC Observables

By looking at the ratio of the first generation left-handed squark over gluino masses in Fig. 2, we already see a potential consequence of the presence of intermediate scale for SUSY collider searches: the configuration $M_3 \approx m_{\tilde{Q}}$, that gives the highest sensitivity at the LHC, could be never reached, since the tendency is to have heavier squarks. However, if this will be the case, no definite conclusion will be extract, since a similar behaviour could be obtained simply by increasing the value of the high energy scalar mass (see the right panels of Fig. 2). On the other hand, if the case $M_3 \approx m_{\tilde{Q}}$ will be observed, this would give an upper bound on α_U and strongly constrain the intermediate scale parameters.

In order to obtain clear information on the intermediate scale physics, observables as much independent as possible of the high energy parameters are necessary. If we assume gaugino mass unification and consider one loop RGEs, the gaugino and first generations sfermion masses can be written as:

$$M_i(M_S) = A_i(M_S, \Delta b, M_I) M_{1/2} \quad (2)$$

$$m_{\tilde{f}}^2(M_S) = m_{\tilde{f}}^2(M_{\text{GUT}}) + B_{\tilde{f}}(M_S, \Delta b, M_I) M_{1/2}^2, \quad (3)$$

where the coefficients A_i and $B_{\tilde{f}}$ are functions of Δb , M_I and M_S . It is then clear that in the combination

$$\Delta_i^{ff'} \equiv \frac{m_{\tilde{f}}^2 - m_{\tilde{f}'}^2}{M_i^2} \quad (4)$$

the explicit dependence on the GUT-scale parameters drops, if $m_{\tilde{f}'}^2(M_{\text{GUT}}) = m_{\tilde{f}}^2(M_{\text{GUT}}) \equiv m_0^2$ as in CMSSM-like scenarios or, more in general, in the case of GUT-symmetric initial conditions (a well-motivated assumption in our setup, as we are requiring unification).

As in Ref. ⁶, where it has been suggested to use these invariants to discriminate among different SUSY seesaw models, we consider the SU(5)-inspired combinations:

$$\Delta_1^{QU} \equiv \frac{m_{\tilde{Q}}^2 - m_{\tilde{U}}^2}{M_1^2}, \quad \Delta_1^{QE} \equiv \frac{m_{\tilde{Q}}^2 - m_{\tilde{E}}^2}{M_1^2}, \quad \Delta_1^{DL} \equiv \frac{m_{\tilde{D}}^2 - m_{\tilde{L}}^2}{M_1^2}. \quad (5)$$

Contours for these quantities on the $(M_I, \Delta b)$ plane are shown in Fig. 3 (taking $M_S = 1$ TeV). As we can see, the invariants rapidly grow for increasing α_U . If the SUSY spectrum will be

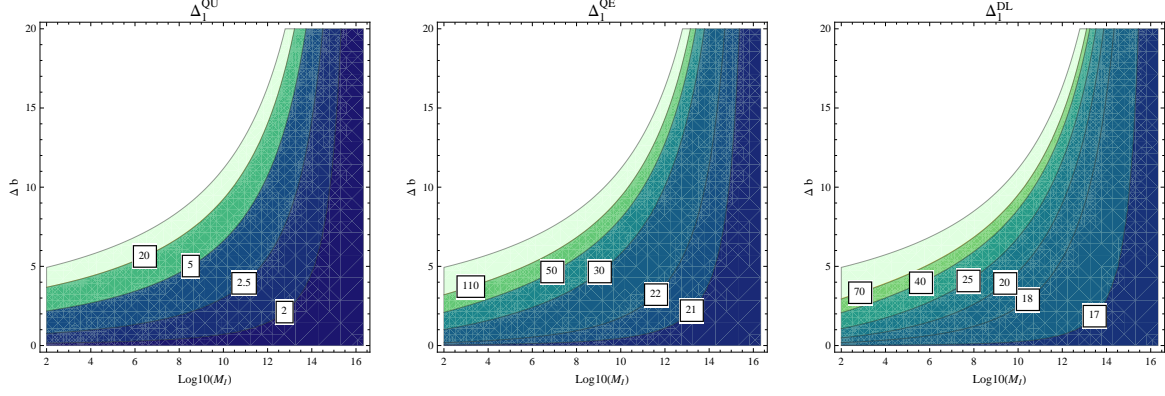


Figure 3: Contours for the mass invariants Δ_1^{QU} , Δ_1^{QE} , Δ_1^{DL} for $M_S = 1\text{TeV}$.

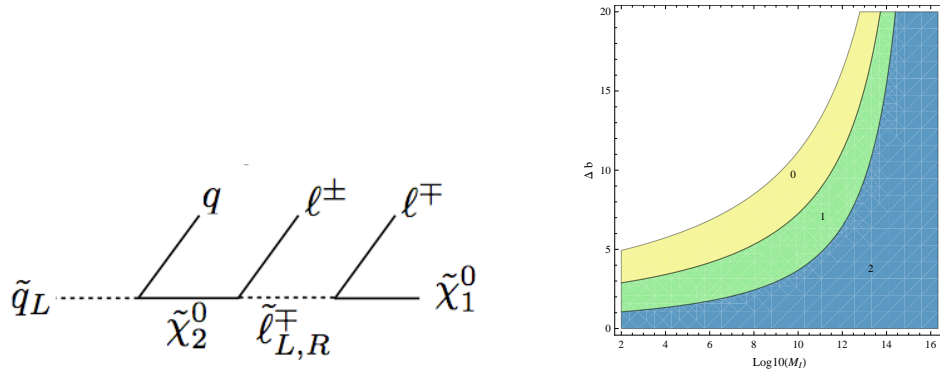


Figure 4: Left panel: an example of cascade decay. Right panel: maximum number of edges.

measured at the LHC with enough precision, from these invariants it should be possible to test if the spectrum is MSSM-like or not, and, in the latter case, even to distinguish between the presence of intermediate scale physics or non-universal boundary conditions, if correlation among these invariants are verified.^a

A possible way to measure sparticle masses at the LHC is through cascade decays like the one depicted in Fig. 4. The intermediate particles are real if

$$m_{\tilde{Q}} > m_{\tilde{\chi}_2^0} > m_{\tilde{\ell}_{L,R}} > m_{\tilde{\chi}_1^0}. \quad (6)$$

In this case the invariant mass distributions of the outgoing SM particles (jets and isolated leptons) exhibit sharp kinematic end-points. By measuring the position of these endpoints in different invariant mass distributions, the masses of the involved sparticles can be measured⁷. The presence of intermediate scale physics moves the position of the edges and, if independent measurements of sparticle masses and edges were available, then important information on the intermediate scale could be extracted.

Moreover, notice that, depending on the spectrum, zero, one or two sharp edges can be present. Indeed, this depends if the above condition is satisfied by both $m_{\tilde{\ell}_L}$ and $m_{\tilde{\ell}_R}$ or by one of them (typically $m_{\tilde{\ell}_R}$) or none. Since the effect of the intermediate scale is precisely that of enhancing the ratio of scalar over gaugino masses, the above inequality will be more hardly satisfied in the presence of intermediate scale physics. In the right panel of Fig. 4 the maximum

^aIn Ref. ⁵ also another set of invariants is considered, namely ratios of differences of scalar masses. These have the advantage of being less dependent on the scale M_S . Analogous plots can be obtained.

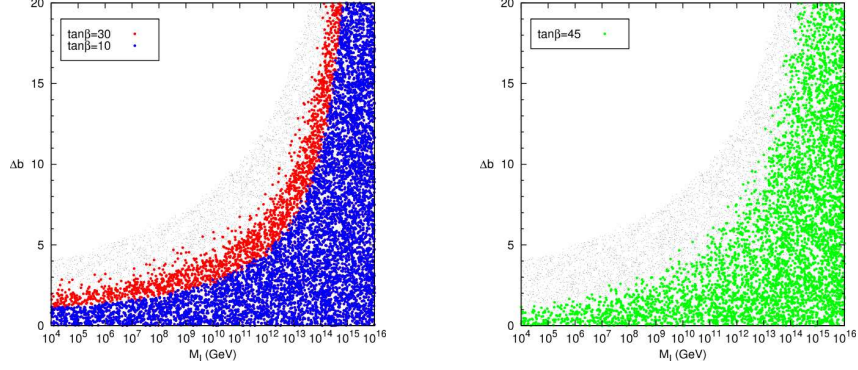


Figure 5: Left: region on the $(M_I, \Delta b)$ plane where the correct relic density for $\tilde{\chi}_1^0$ is obtained via $\tilde{\tau}$ coannihilation (blue points corresponds to $\tan \beta = 10$, red to $\tan \beta = 30$). Right: the same for the A-funnel region.

number of edges on the plane $(M_I, \Delta b)$ is depicted. It is then clear that the observation of two or one edge in the mass invariant distributions would rule out a large portion of parameter space.

4 Neutralino Dark Matter

The modification of the SUSY spectrum described in the previous sections can destabilise the regions of the parameter space where precise relations among the parameters are required in order to fulfill the WMAP bound on DM relic abundance. Indeed the lightest neutralino χ_1^0 is overproduced in the early universe and the measured DM relic density is not obtained unless the neutralino (co)annihilation cross section is enhanced by particular conditions. Such conditions define few regions in the parameter space where the WMAP bound is satisfied: (i) the $\tilde{\tau}$ coannihilation region, where the correct relic density is achieved thanks to an efficient $\tilde{\tau}$ - $\tilde{\chi}_1^0$ coannihilation, which requires $m_{\tilde{\tau}_1} \approx m_{\tilde{\chi}_1^0}$; (ii) the “focus-point” region, where the Higgsino-component of $\tilde{\chi}_1^0$ is sizable, i.e. $\mu \approx M_1$; (iii) the A-funnel region, where the neutralino annihilation is enhanced by a resonant s-channel CP-odd Higgs exchange, if $m_A \simeq 2 \times m_{\tilde{\chi}_1^0}$. Notice that typically the neutralino is \tilde{B} -like, which means $m_{\tilde{\chi}_1^0} \approx M_1$. Then it is clear that, since the intermediate scale tends to increase the ratio of scalar over gaugino masses, the high-energy parameter space regions where the above conditions are satisfied will be distorted and could eventually disappear.

We first consider the $\tilde{\tau}$ coannihilation region. In the constrained MSSM it usually corresponds to a thin strip on the border of an area excluded because it gives a $\tilde{\tau}$ lightest SUSY particle. It has already been noticed in specific models^{8,9,3,4,10} that the introduction of new physics at intermediate scale distorts this region. If the effect is large enough the $\tilde{\tau}$ will never be lighter than χ_1^0 and the coannihilation region will disappear. In the left panel of Fig. 5 the blue points represent the area on the $(M_I, \Delta b)$ plane where the coannihilation is possible for $\tan \beta = 10$, while the red ones correspond to $\tan \beta = 30$ (grey dots correspond to the region allowed by the perturbativity bounds).^b Even if the allowed area can be enlarged for even higher $\tan \beta$, for $\alpha_U \geq 0.1$ the coannihilation region will anyway disappear.

A similar fate will follow the A-funnel region, as it is shown in the right panel of Fig. 5 for $\tan \beta = 45$. Indeed in this case the mass of the CP-odd scalar Higgs is given by $m_A^2 \approx m_{H_d}^2 - m_{H_u}^2$ and, since the ratios $|m_{H_{u,d}}^2|/M_1$ grow with α_U , m_A/M_1 gets increased too. Again, for large enough α_U , the correct neutralino relic density cannot be obtained with such a mechanism.

The situation with the focus point region is a bit different. Even if the intermediate scale tends generically to increase the ratio μ/M_1 rendering the neutralino more and more \tilde{B} -like, it is always possible to find configurations with $\mu \approx M_1$, such that the Higgsino component of

^bThe results of this section have been obtained performing numerical two loops computations.

$\tilde{\chi}_1^0$ is sufficiently large to give a sizeable annihilation cross-section. The focus point region is therefore the only DM branch which is not destabilised by the intermediate scale, if CMSSM-like boundary conditions are assumed.

5 Conclusions

In this talk we have discussed the main consequences of the presence of chiral superfields at a scale intermediate between the EW and the GUT scale. The main effect is the increment of the unified gauge coupling, which causes the increment of the ratio of scalar over gaugino masses. This has interesting phenomenological consequences that we have discussed here. In particular it destabilises the regions of the parameter space where the correct DM relic density can be achieved; only the focus-point region is practically unaffected. The presence of such new physics can be tested indirectly at the LHC by looking at the (number of) edges in cascade decays and/or by building mass invariants, once the sparticle spectrum is measured. Therefore we have shown that precious information, i.e. mainly constraints, on intermediate scale physics can be obtained by considering the appropriate low energy observables.

Acknowledgments

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